SITES OF FAILURE IN MUSCLE FATIGUE

Li-Qun Zhang[1-4] and William Z. Rymer[1,2,4]
[1]Sensory Motor Performance Program, Rehabilitation Institute of Chicago
Departments of [2]Physical Medicine and Rehabilitation, [3]Orthopaedic Surgery, and [4]Biomedical Engineering
Northwestern University, 345 E. Superior St., Chicago, IL 60611, USA

Abstract- **The sites of failure in muscle fatigue were investigated by applying controlled tapping to a muscle tendon before and after fatigue of the muscle. The resulting reflex responses were evaluated to assess muscle activation (using the EMG signal for activation failure) and joint torque (for contractile failure). An instrumented hammer was used to tap the triceps muscle tendon and record the tapping force, while the triceps EMG signal and reflex joint torque were recorded to provide measures of the reflex responses. Elbow extensor muscle fatigue was induced through repeated voluntary isometric contraction. The subject generated elbow extension torque in a 6 sec on and 4 sec off pattern for 15 minutes. A rest period of ten minutes was used to let the acute fatiguing effects diminish. Identical tendon tapping tests were done before and after fatigue. Tendon reflex gain (calculated from the tapping force input to the reflex torque output) and tapping-induced EMG gain (calculated from the tapping force input to the reflex-mediated EMG output) were used to characterize tendon reflexes. Following fatigue, we recorded substantial reductions in maximal voluntary elbow extension torque, which was more severe in some subjects than in others. It was found that less severe muscle fatigue was associated only with contractile failure, as indicated by reduction in elbow extension torque but not in EMG response to the controlled tendon tapping. More severe fatigue was associated with both activation and contractile failures, as indicated by reductions in both EMG and joint torque responses to the controlled tendon tapping. The controlled tendon tapping minimized the variations in central drive to motor neurons and neural strategy associated with voluntary contractions and evaluation of the induced reflex EMG and joint torque helps us better understand the underlying mechanisms and sites associated with muscle fatigue.**

***Keywords* - Fatigue, failure, site, muscle.**

I. INTRODUCTION

Neuromuscular fatigue impairs the force generating capacity of muscles and it is experienced commonly in normal everyday physical exercise and especially in neuromuscular diseases. Despite significant progress in research on muscle fatigue, “remarkably little is known of the mechanisms underlying neuromuscular fatigue during human voluntary contraction, or at which of the possible sites it occurs” [1]. Multiple mechanisms may be responsible for muscle fatigue, and different sites in the neuromuscular system may fail during different tasks involving muscle fatigue [2]. Furthermore, different sites may be involved in a task as fatigue progresses.

The objective of this study was to investigate the sites of failure in muscle fatigue. Controlled tendon tapping was used to induce reflex responses measured by muscle EMG signal and joint torque, which in turn were used to evaluate activation failure and contractile failure, respectively.

II. METHODOLOGY

Four subjects with no prior history of neurological disorders or musculoskeletal injuries participated in this study. The study was approved by the Institutional Review Board of Northwestern University. All subjects gave informed consent before the experiment.

A. Experimental Setup

The subject was seated in an elbow-driving device with the shoulder abducted to 90º. The distal forearm, wrist and proximal hand of the subject were cast and secured to a motor shaft through an aluminum beam located underneath the forearm. The motor shaft was perpendicular to the ground and was aligned with the elbow flexion axis (Fig. 1). The elbow-driving device was locked at a selected elbow flexion angle, and tendon tapping was done with the elbow at isometric condition.

With the elbow joint fixed at 90º flexion, a spot on the triceps tendon most sensitive to tendon tapping (with the strongest reflex response) was located using a regular tendon-tapping hammer. A self-adhesive rubber bumper was then pressed onto the most sensitive spot. The bumper had a hemisphere shape and was about 1 cm in diameter. It served the following functions. First, it transmitted the tapping force evenly onto the most sensitive spot of the triceps muscle tendon and also onto the force sensor. Second, it acted as a large and elevated target, which was much easier to hit accurately with the large flat surface of the hammerhead. Third, the bumper prevented direct contact of the plastic hammerhead with the tendon, which could cause discomfort with prolonged stimulation.

An instrumented hammer with a force sensor mounted at its head was used to tap the triceps tendon through the rubber pad and record the tapping force.

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25 Oct 2001	N/A	-

Title and Subtitle Sites of Failure in Muscle Fatigue	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Sensory Motor Performance Program Rehabilitation Institute of Chicago Chicago, IL 60611	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes Papers from 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference cd-rom.	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 4	

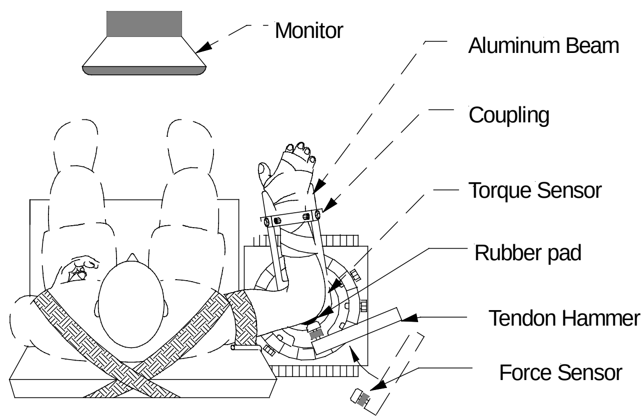

Fig. 1. Experimental setup for investigating site of failure in fatigue through evaluating tendon reflexes. The distal forearm and wrist were cast and fixed to an aluminum beam, which was in turn fixed to a motor shaft through a torque sensor. The motor was locked at 90° elbow flexion and the triceps muscle tendon was tapped with an instrumented hammer.

B. Induction of Muscle Fatigue

Muscle fatigue was induced through intermittent submaximal voluntary contraction [3, 4]. A target torque was displayed on a computer monitor and the subject was asked to generate a specified level of target torque isometrically during the "on" period. The on-and-off cycle was ten seconds long and the "on" and "off" portions lasted six and four seconds respectively. The initial target torque level was about 60% of the elbow extension MVC. The measured elbow extension torque was displayed together with the target torque on the computer screen in real time, and the computer cued the "on" periods with an auditory signal. Each exercise session lasted six minutes. After a rest of two minutes, the next exercise session started at a lower target torque level as the muscle got fatigued. In total, two and one-half sessions or 15 minutes exhausting elbow extension exercises were used to fatigue the elbow extensor muscles severely.

Since the fatigue studied here was primarily the long-lasting contractile fatigue, a rest period of ten minutes was used to let the acute fatiguing effects diminish. These acute effects included reduction of fiber conduction velocity and shift of EMG power spectra toward lower frequencies. It has been shown that the acute effects diminished in about 10 min after the completion of fatiguing contraction [5], while significant contractile fatigue lasted for about several hours. In fact, since the fatigue induced was rather severe, the subjects often experienced subsequent muscle soreness.

C. Protocol

The elbow joint was rotated to a selected flexion angle (90°) and the device was locked at the position. The subject was asked to fully relax during each tendon tapping trial and not to react/anticipate to the taps. At the beginning of the experiment, tapping force was gradually increased until significant triceps muscle contraction was elicited. Repeated tapping was then delivered around the appropriate force level. During each 20 sec long trial, tendon tapping was applied at a randomly selected time for about six times, and about three tapping trials were collected. A brief rest of about 15 seconds was taken between trials.

Surface electrodes were used to record EMG signal from the lateral, medial and long heads of the triceps muscle. After lowpass filtering (8^{th}-order Butterworth filters with 230 Hz cutoff frequency), the tendon-tapping force, EMG signals, and knee joint extension torque were sampled by a computer at 500 Hz. The EMG signals were also high-pass filtered (5 Hz cutoff).

Isometric maximum voluntary contraction (MVC) was measured at the beginning of the experiment to quantify the muscle strength in elbow extension. Three trials were repeated and the maximum torque reached during the trials was taken as the muscle strength.

Muscle fatigue was then induced through voluntary intermittent isometric contraction, lasting about 15 minutes. Afterwards, the same tendon tapping and MVC tests were repeated. The elbow extension torque, tapping force (for tendon tapping only), and triceps EMG signals were recorded during the tendon tapping and MVC tests.

D. Data Analysis

Since the reflex torque increased with the tendon tapping force within a range of tapping force, it was reasonable to characterize them jointly. The impulse response was used to characterize the tendon reflex system with the reflex torque and tapping force as system output and input, respectively. Since the tapping force was rather brief, it could be approximated as a pulse. Therefore, the impulse response $h_{Mf}(t)$ could be easily approximated as the reflex torque response $M(\tau)$ scaled by the area of the tapping force pulse $f(\tau)$ [6]:

$$h_{Mf}(t) = \frac{M(t)}{\sum_{\tau} f(\tau)} \tag{1}$$

Tendon reflex gain (G_{tr}), the system gain from the tendon tapping force to the reflex torque, was estimated from the peak value of the impulse response. Physically, G_{tr} could be interpreted as the moment arm used to produce the reflex torque.

Similar impulse response was defined for the system with tapping force and reflex-mediated muscle EMG signals as input and output, respectively:

$$h_{muscle}(t) = \frac{EMG_{muscle}(t)}{\sum_{\tau} f(\tau)} \tag{2}$$

The tapping-induced EMG gain, G_{muscle}, was estimated from the peak value of the impulse response in Eq. (2).

III. RESULTS

The intermittent isometric contraction was rather effective in inducing muscle fatigue. Maximal voluntary elbow extension torque was reduced substantially after the fatiguing exercise. Different subjects were fatigued to different degrees, and the extension MVC reduction ranged from 40% to 66%.

Tendon reflex gain for relaxed muscles was reduced considerably after fatigue (Figs. 2 and 3). From top to bottom, the three rows showed the tendon tapping force, EMG signal from the triceps muscle, and the elbow extension torque response, respectively. The left and right columns corresponded to the pre- and post-fatigue conditions, respectively. As shown in the figures, the pre- and post-fatigue tendon tapping forces were similar to each other. In contrast, the post-fatigue reflex torque at the elbow joint was significantly lower than its pre-fatigue counterpart. Accordingly, Student t-test showed that tendon reflex gain was reduced significantly ($p < 0.001$).

Notice that for the two subplots in the bottom row of Figs. 2 and 3, the brief torque pulse (or oscillation) immediately following the tendon tapping was not due to the reflex action. Instead, it was caused by the mechanical tapping impact onto the humerus and the elbow joint. The subsequent, slow and longer lasting twitching moment was reflex-mediated response.

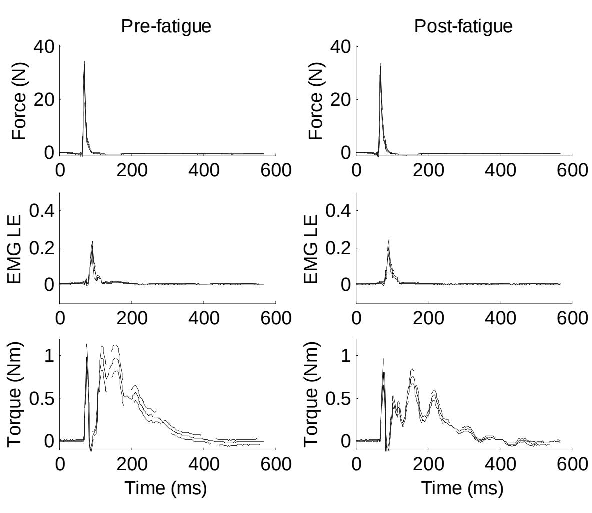

Fig. 2. Tendon tapping results averaged over multiple taps on the triceps muscle tendon of a right elbow joint. From top to bottom, the three rows show the tendon tapping force, triceps muscle EMG linear envelope (LE), and elbow extension torque, respectively. The positive direction of the elbow torque in the bottom row corresponds to active elbow extensor contraction. The left and right columns correspond to pre- and post-fatigue conditions respectively. The solid and dashed lines give the mean and mean ± σ (standard deviation) of each signal, respectively. The number of taps for the pre- and post-fatigue conditions was 10 and 11, respectively.

The EMG signal in Figs. 2 and 3 showed that activation failure occurred when the muscle was fatigued more severely. The subject in Fig. 2 had a 42% reduction of elbow extension MVC after fatigue, while the one in Fig. 3 had 66% MVC reduction. Although the reflex torque and tendon reflex gain G_{tr} were reduced significantly in both cases, reflex EMG response and G_{muscle} for the controlled tapping were only reduced significantly in the more severely fatigued muscle (Fig. 3, $p<0.001$).

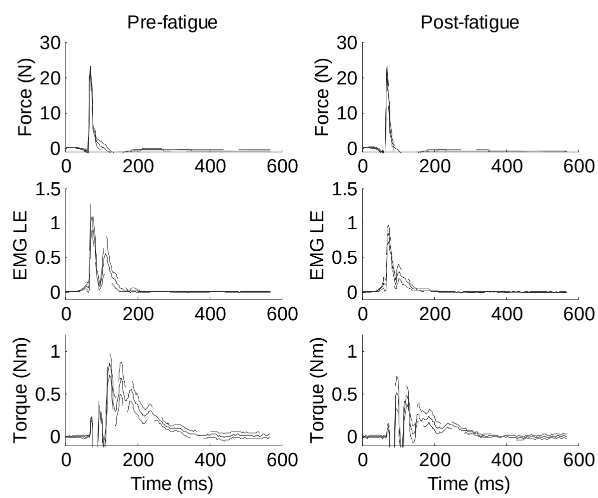

Fig. 3. Tendon tapping results averaged over multiple taps on the triceps muscle tendon of a right elbow joint. From top to bottom, the three rows show the tendon tapping force, triceps muscle EMG linear envelope (LE), and elbow extension torque, respectively. The positive direction of the elbow torque in the bottom row corresponds to active elbow extensor contraction. The left and right columns correspond to pre- and post-fatigue conditions respectively. The solid and dashed lines give the mean and mean ± σ of each of the signals, respectively. The number of taps for the pre- and post-fatigue conditions was 14 and 10, respectively.

IV. DISCUSSION

The study provided us a useful tool to evaluate the sites of failure in muscle fatigue and helps us gain insight into the mechanisms underlying muscle fatigue. The small amplitude perturbation (tendon tapping) provided us an objective and controlled method to stimulate the neuromuscular system, and the EMG and torque recordings allowed us to investigate activation failure and contractile failure (excitation-contraction coupling failure) involved in muscle fatigue, respectively. Less severe fatigue was associated with contractile failure only as indicated by reduction in elbow extension torque but not in EMG response to the controlled tendon tapping. More severe fatigue was associated with both activation and contractile failure, as indicated by reductions in both EMG and joint torque responses to the controlled tendon tapping input. The study helps us gain insights into the mechanisms underlying muscle fatigue.

Of note is that the activation failure assessed in this study could be due to failure at multiple sites. First, it could be due to failure in neuromuscular propagation from the efferent nerves to muscle fibers. Second, it could be due to failure at the motor neurons in the spinal cord, which in turn could be due to a decreased response to the same stimulus (gain reduction) or an increased threshold to the stimulus following fatigue. Third, it could also be due to decreased afferent signal propagation from the stretched spindles to motor neurons. Furthermore, fatigue-induced failures could occur at multiple sites and different sites might contribute to the overall muscle fatigue differently, dependent on the tasks performed and the degree of fatigue.

A difficulty involved in muscle fatigue studies is the uncertainty associated with the determination of muscle strength, which could be affected markedly by subjects' motivation and skill in performing maximal voluntary contractions [2]. The controlled tendon tapping used in this study minimized such uncertainty in central nervous system drives to motor neurons and provided us objective and quantitative technique to stimulate the neuromuscular system and evaluate muscle fatigue.

The M-wave has been used to evaluate muscle fatigue in neuromuscular propagation [2, 7-11]. Both the M-wave based approach and the above approach based on tendon tapping allow us to evaluate muscle fatigue with controlled stimuli (electrical stimulation and tendon tapping for the two cases respectively). The M-wave evaluates propagation between the site of initiation (nerves) and the site of recording (muscle fibers), while the tendon-tapping based approach evaluates the afferent pathway, motor neuron excitability as well as neuromuscular propagation. Further work can be done to combine the different approaches to better understand the underlying mechanisms and sites of failure associated with muscle fatigue.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the NIH, the Whitaker Foundation, and the Falk Medical Research Trust.

REFERENCES

[1] B. R. Bigland-Ritchie and J. J. Woods, "Changes in muscle contractile properties and neural control during human muscular fatigue," *Muscle & Nerve*, vol. 7, pp. 691-699, 1984.

[2] R. M. Enoka and D. G. Stuart, "Neurobiology of Muscle Fatigue," *J. Appl. Physiol.*, vol. 72, pp. 1631-1648, 1992.

[3] B. R. Bigland-Ritchie, F. Furbush, and J. J. Woods, "Fatigue of intermittent submaximal voluntary contractions: central and peripheral factors," *J. Appl. Physiol.*, vol. 61, pp. 421-429, 1986.

[4] L.-Q. Zhang and W. Z. Rymer, "Intrinsic and Reflex Changes Induced by Fatigue of the Human Elbow Extensor Muscles," *J. Neurophysiol.*, in press, 2001.

[5] R. F. Kirsch and W. Z. Rymer, "Neural Compensation for Muscle Fatigue: Evidence for Significant Force Regulation in Man," *J. Neurophysiol*, vol. 57, pp. 1893-1910, 1987.

[6] L.-Q. Zhang, H. Huang, J. A. Sliwa, and W. Z. Rymer, "System Identification of Tendon Reflex Dynamics," *IEEE Trans. Rehab. Eng.*, vol. 7, pp. 193-203, 1999.

[7] B. R. Bigland-Ritchie, C. G. Kukulka, O. C. J. Lippold, and J. J. Woods, "The absence of neuromuscular transmission failure in sustained maximal voluntary contractions," *J. Physiol. (London)*, vol. 330, pp. 265-278, 1982.

[8] F. Bellemare and N. Garzaniti, "Failure of neuromuscular propagation during human maximal voluntary contraction," *J. Appl. Physiol.*, vol. 64, pp. 1084-1093, 1988.

[9] C. G. Kukulka, A. G. Russell, and M. A. Moore, "Electrical and mechanical changes in human soleus muscle during sustained maximal isometric contractions," *Brain Research*, vol. 362, pp. 47-54, 1986.

[10] H. S. Milner-Brown and R. G. Miller, "Muscle membrane excitation and impulse propagation velocity are reduced during muscle fatigue," *Muscle & Nerve*, vol. 9, pp. 367-374, 1986.

[11] J. A. Stephens and A. Taylor, "Fatigue of maintained voluntary muscle contraction in man," *J. Physiol. (London)*, vol. 220, pp. 1-18, 1972.